METEOROLOGICAL OFFICE Met.O.762

THE METEOROLOGICAL MAGAZINE

Vol. 94, No. 1117, August 1965

551.508.71:551.524:551.571

THE EFFECT OF CONTAMINATED MUSLINS AND WICKS ON WET-BULB TEMPERATURE READINGS

By W. D. S. McCAFFERY

Summary.—This paper describes an experiment made to discover the effect on readings of a wet-bulb thermometer of leaving the muslin and wick fitted to the instrument for long periods (up to six months), and gives some conclusions drawn from the results. The conclusions are used to suggest for how long instruments exposed on masts 1000 feet or more in height may be left unattended (provided an adequate water supply is maintained). A detailed discussion of the results is given in an unpublished paper, *Wet-bulb temperatures—a comparison between readings from clean and dirty instruments*, by W. D. S. McCaffery; this paper is available on loan from the Meteorological Office Library.

Introduction.—A method of obtaining profiles of temperature, humidity and wind in the lowest 1000 feet or so of the atmosphere is to mount instruments at several levels on tall masts. Instruments so mounted are not always readily accessible for maintenance, consequently it is of some interest to study how atmospheric pollution of all sorts, accumulating on unchanged muslins and wicks of wet-bulb thermometers, affects the readings of the instruments.

Measurements made by Lawrence,[1,2] suggest a variation of atmospheric pollution with height, the level of maximum concentration being related to the height of pollution sources (e.g. chimneys) in the area. The measurements were made, not in the free atmosphere, but near the ground at sites up a steeply sloping hillside; the results, nevertheless, may be significant close to sources of pollution and in hilly districts where the level of maximum concentration may depend on the height of hills between the source and the site of the measuring instruments.

Lawrence also found a seasonal change in the vertical distribution of atmospheric pollution, the pollution in winter being approximately twice that measured in summer at heights up to about 1200 feet above MSL (about 700 feet above valley level).

Another result reported by Lawrence is the direct dependence of accumulated pollution on the run-of-wind. The flow of air through a screen, especially a single-louvered screen, at heights up to several hundreds of feet above ground level is likely to be significantly different, in the mean, from the flow of air through a standard thermometer screen housing instruments at 4 feet above the ground. Consequently the dirtying of a wet-bulb muslin and wick at a hundred or more feet above ground level may proceed much faster than at the ground.

It follows that the length of time a wet-bulb muslin and wick may reasonably be left unchanged, depends on the height of the instrument above the ground and the effectiveness of the sheltering screen in regulating the flow of air past the thermometer bulb. Other important factors are the surrounding topography and pollution sources, season of the year, direction and speed of the mean wind, and also significant departures from the mean on particular occasions. Lawrence's measurements were made in a hilly district away from the sea in Lancashire at Helmshore, a rural site almost encircled by industrial areas of Lancashire and the West Riding of Yorkshire. His results, therefore, may not be valid in coastal regions where, with winds off the sea, the pollution is different and the source is at the surface; nor may they be entirely valid in relatively flat inland areas. The required answer may be obtained, ideally, only by testing at each observing level at each mast site.

In the absence of data from masts, and because the method was simple and easy to organize, tests were arranged with instruments exposed at the standard height of 4 feet in thermometer screens at ground level.

Acceptable practice for ensuring a suitable standard of cleanliness, and hence of accuracy, of wet-bulb thermometers exposed in thermometer screens, is described in standard reference sources.[3,4] Experiments to determine the rate and extent of the deterioration in efficiency of a wet-bulb thermometer have been made by Sutcliffe,[5] Garnett[6] and Durward,[7] while other relevant experiments have been described by Whipple[8,9] and elsewhere in the *Meteorological Magazine.*[10] The present experiment extends such work to a number of varied locations, including rural, semi-rural and urban areas, coastal areas and ships at sea.

Nature of the experiment and stations participating.—At each station a second wet-bulb thermometer was suspended from the roof of the thermometer screen closely alongside the standard wet-bulb instrument, which was maintained in the usual way and referred to as the clean wet-bulb (*C*). Once the second wet-bulb thermometer was mounted in the screen, the muslin and wick were left unchanged throughout the course of the experiment, the thermometer being referred to as the dirty wet-bulb (*D*). The experiment commenced at Bracknell on 8 January 1964 and was soon extended to Kew where readings began on 5 February. At Bracknell readings were recorded at 0900 GMT on five days each week; at Kew readings were recorded daily at 0900 GMT, and on most days at 1200 and 1500 GMT as well.

After nearly 11 weeks at Bracknell and 7 weeks at Kew, during which time only occasional differences of 0·1°C, and very occasional differences of 0·2°C or 0·3°C were observed between the two wet-bulb readings, it was decided that the results justified extending the experiment to include records from areas where the effects of industrial and urban pollution might be greater than at Kew, and also to examine the effects of proximity to the sea. The stations listed in Table I were selected to participate in the experiment, most of them commencing the comparison of readings early in April 1964. At this stage the co-operation of the Marine Branch of the Meteorological Office was invited and as a result arrangements were made for two Ocean Weather Ships to take part, returns being received from OWS *Weather Surveyor* and OWS *Weather Monitor* covering voyages made between May and October 1964.

TABLE I—STATIONS PARTICIPATING IN THE EXPERIMENT

Bracknell	Initial pilot experiment
Kew	Initial urban area station
Eskdalemuir	Clean air station
Birmingham Airport	Urban/industrial area station
London Weather Centre	,, ,, ,, ,,
Manchester Weather Centre	,, ,, ,, ,,
Acklington	Coastal or near coastal station
Benbecula	,, ,, ,, ,, ,,
Leuchars	,, ,, ,, ,, ,,
Mount Batten	,, ,, ,, ,, ,,
Valley	,, ,, ,, ,, ,,
Wick	,, ,, ,, ,, ,,
Weather Monitor	Ocean Weather Ship
Weather Surveyor	,, ,, ,,

Participating stations were asked to make returns of corrected temperature readings made at 0600 and 1500 GMT—times likely to be near periods of maximum and minimum relative humidity—and also at other times during the day if the difference, *D–C* between readings of the dirty and clean wet-bulb thermometers was greater than that recorded at either 0600 or 1500. Wind speed and direction were also listed and any relevant remarks. Readings were continued until 31 October 1964. At Bracknell, after approximately 6 months, the dirty muslin and wick were replaced by a clean set on 1 July and a second series of readings was started. At Manchester Weather Centre a similar change was made on 8 July. At all the other land stations the muslin and wick on the dirty wet-bulb thermometer were left unchanged throughout the experiment.

Ocean Weather Ship *Weather Surveyor* made three voyages between May and September 1964 with the same muslin and wick on the second wet-bulb thermometer. The (portable) marine-type thermometer screen was removed inside during spells in harbour. A fourth voyage was made in September/October with new equipment and with clean muslins and wicks on both wet-bulb instruments at the beginning of the voyage.

Ocean Weather Ship *Weather Monitor* also made four voyages between May and October. On this ship clean muslins and wicks were fitted at the beginning of all four voyages. New thermometers and screens were fitted for the fourth voyage.

Sources of error in psychrometry.—The determination of humidity with a psychrometer depends on the measured air temperature and the temperature depression of the wet element. The uncertainty in the derived relative humidity (or dew-point) is due principally to that in the temperature depression. For example, at 10°C, with a true depression of 5°C, a one degree error in dry-bulb temperature leads to an error in relative humidity of about 2 per cent while a one degree error in temperature depression yields an error of about 12 per cent. At the same dry-bulb temperature, corresponding errors in dew-point are approximately 1·5°C and 4°C, with errors in the depression of the dew-point below the dry-bulb reading—which is of importance to the forecaster—of 0·5°C and 4°C. The magnitude of the error in relative humidity, for a given error in depression of the wet bulb, increases with decrease in dry-bulb temperature, the increase becoming marked at temperatures near and below 0°C. Thus, for a certain error in wet-bulb depression, the resulting error in relative humidity may be acceptable at dry-bulb temperatures greater than a particular value, but not at temperatures lower than such a value. Table II shows the approximate change in relative humidity and in dew-point for a change in the wet-bulb temperature of 0·5°C at different dry-bulb temperatures.

TABLE II—APPROXIMATE CHANGE IN RELATIVE HUMIDITY AND IN DEW-POINT WHEN THE WET-BULB DEPRESSION CHANGES BY 0·5°C

Dry bulb °C	Change in relative humidity *per cent*	Change in dew-point °C
20	4	1
15	5	1
10	6	1
5	8	2
0	10	2
−5	13	3
−10	18	4

Errors occurring in the temperature depression are of two kinds, those which are effectively equal to a constant fraction of the temperature depression and those which form a constant additive part of the depression. Errors of the first kind may be unimportant at high humidities while being serious at low humidities; errors of the second kind may be important at all humidities. The forecaster is most interested in accurate measurements of high humidities, though climatologists and others may wish for a similar accuracy at all values of humidity.

A detailed list of errors in psychrometry is given by Wylie.[11] Those most likely to be significant in measurements made in thermometer screens are due to:

(i) Inadequacy or imperfection of the covering of the wet bulb and of the water supply to it,

(ii) The presence of substances which affect the vapour pressure over the water on the wet bulb,

(iii) Variation of the assumed rate of ventilation (due to opening of the screen door and/or length of time it is left open);

(iv) The temperature of the wet bulb influencing that of the dry either by free or forced convection, or by radiation;

(v) Temperature gradients in the neighbourhood of the wet and dry elements;

(vi) A high rate of change of atmospheric conditions (involving the time lag of the thermometers).

The last two sources of error lead to errors of the second kind mentioned above, the others give rise to errors of the first kind.

The object of the experiment was to discover the time taken for errors due to (i) and (ii) above to become significant. The interpretation of the results is complicated by the presence of errors due to other causes.

Results of the experiment.—A detailed discussion of the results is available elsewhere[12] and only a brief account will be given here.

Errors in psychrometry (apart from ventilation errors and errors in the thermometers themselves) operate in such a direction as to increase the observed relative humidity.[13] Increasing pollution (of the dirty instrument) should therefore lead to increasingly positive differences *D–C*. While there was some evidence that this in fact occurred, practically all stations recorded numerous occasions when the depression of the dirty wet-bulb thermometer was greater than that of the clean. A close examination of the results, in conjunction with the examination of hygrograph records, indicated that some, but not all, of the negative values for *D–C* occurred on occasions of rapidly changing humidity and could be accounted for by assuming a difference in the lag coefficients of the clean and dirty instruments.

At some stations negative values of *D–C* recurred after a long series of increasing positive ones. It was also noticed at other stations, notably Kew Observatory, that after a period of increasing positive *D–C* values over a period of some weeks a sudden and marked improvement in the efficiency of the dirty instrument occurred with much reduced positive values of *D–C*.

Apart from the somewhat anomalous results mentioned above, the most surprising result of the experiment was the length of time the dirty instruments remained reasonably efficient, with errors no greater than those which from time to time occur in wet-bulb instruments treated according to standard practice. It is also surprising that even after the muslin on a wet-bulb thermometer becomes visibly polluted the resulting errors may be very small. In smoky areas, errors can become large, but nevertheless may remain quite small for long periods of time. The most consistent results, with only small differences between the two wet-bulb thermometers, were obtained from Eskdalemuir, but results were nearly as good from Bracknell and Kew. London Weather Centre showed a greater range in the recorded *D–C* values, especially at first, but only a very slight increase in the weekly root-mean-square *D–C* value over a period of 30 weeks.

Results from Manchester Weather Centre and Birmingham Airport showed a more rapid and larger decrease in efficiency of the dirty wet-bulb thermometer at these stations when compared with the results mentioned above, the instrument at Manchester tending to act more like a dry-bulb thermometer after about 9 weeks.

From the coastal stations taking part in the experiment the results lay somewhere between those from the two groups of stations already mentioned, none of the instruments showing the very marked decrease in efficiency characteristic of the later stages of the experiment at Manchester and Birmingham. A feature of the results was the numerous reports, on occasions of high humidity, of the dirty wet-bulb thermometer reading higher than the dry-bulb thermometer; an explanation of this phenomenon is given by Gregory and Rourke[14] on the basis that the saturated vapour pressure over a solution is less than that over a pure solvent and may even be less than the atmospheric vapour pressure.

Results from the weather ships were rather varied, indicating difficulties of obtaining satisfactory exposure and ventilation as well as variation in pollution rates with different wind and sea conditions. The results also indicated that for several weeks errors in readings from the dirty wet-bulb thermometer may be no bigger, though occurring more frequently, than those occurring on the first day of fitting a clean muslin and wick to the standard instrument.

Sometimes quite large errors can occur in readings of temperature and humidity made by experienced observers following standard practice. In an experiment carried out at Valley and Birmingham Airport over a period of 17 weeks, the differences between two quick readings of both the dry-bulb and wet-bulb thermometers were found to be $\geqslant 0{\cdot}1$°C on 308 occasions and $>0{\cdot}4$°C on 10 occasions.

Effective life of muslin and wick.—The experiment described was primarily an attempt to obtain information on how long a muslin and wick on a wet-bulb thermometer may be left unchanged without introducing unacceptable errors. For thermometers exposed in thermometer screens at ground level the results enable an estimate to be given dependent on some assumptions about the type of pollution. From these results we may infer how instruments exposed on tall masts 1000 feet or more in height may possibly be affected.

Where pollution concentration is very small (Eskdalemuir) errors are negligible for some weeks, and small, 3 or 4 per cent at 50 per cent relative humidity, after two or three months. There is no indication, even after 5 or 6 months, of the instrument becoming completely inefficient. At the other extreme (Manchester), where pollution is industrial or urban in origin, the wet bulb may completely fail to function after about 9 weeks and is probably too inefficient to be of use to the forecaster after about 3 or 4 weeks (though errors from other sources make this difficult to estimate). For inland stations, between these two extremes, returns from Bracknell, Kew, London Weather Centre and Birmingham Airport suggest that pollution effects may not become a source of error important to forecasters within a period of 2 or 3 months. (That London Weather Centre is like Kew rather than like Manchester Weather Centre may possibly be a result of the Clean Air Act. A report on the investigation of atmospheric pollution by the Department of Scientific and Industrial Research [15] shows that smoke concentrations in the vicinity of Kew and London Weather Centre are similar.)

The returns from coastal stations and the weather ships show a wide variation in the rate at which effects likely to be due to the accumulation of salt pollution become significant, and clearly wind speed and, at a coastal station, wind direction are important. Except, however, for instruments at the foot of a mast on or very near the coastline, the accumulation of salt on instruments several hundred feet above ground level is likely to be slow.

It may be inferred, therefore, that wet-bulb thermometers exposed on tall masts situated in areas not in the immediate neighbourhood of sources of heavy industrial pollution, are likely to remain effective instruments for up to 1 month or more and may retain an efficiency acceptable to forecasters for periods as long as 2 or 3 months, provided an adequate water supply is maintained.

Acknowledgement.—This experiment would not have been possible without the willing co-operation of the staff at Meteorological Office outstations and on Ocean Weather Ships, some of whom made helpful suggestions on the design of the experiment and the interpretation and analysis of the data.

REFERENCES

1. LAWRENCE, E. N.; Atmospheric pollution (sulphur dioxide) in hilly terrain. *Int. J. Air Wat. Poll., London*, **6**, 1962, p.5.

2. LAWRENCE, E. N.; The measurement of atmospheric sulphur compounds using lead dioxide. *Int. J. Air. Wat. Poll., London,* **8,** 1964, p.381.
3. London, Meteorological Office. Handbook of meteorological instruments: Part I. London, HMSO, 1956.
4. London, Meteorological Office. Observer's handbook. London, HMSO, 1956.
5. SUTCLIFFE, R. C.; Renewal of the wick and muslin of a wet bulb thermometer. *Met. Mag., London,* **63,** 1928, p.142.
6. GARNETT, H.; Contamination of the wick and muslin of wet-bulbs at coastal stations. *Met. Mag., London,* **64,** 1929, p.132.
7. DURWARD, J.; Renewal of muslin and wick on wet-bulb thermometers. *Met. Mag., London,* **63,** 1928, p.205.
8. WHIPPLE, F. J. W.; Experiments with wet-bulb thermometers. *Met. Mag., London,* **63,** 1928, p.253.
9. WHIPPLE, F. J. W.; Experiments with wet-bulb thermometers. *Met. Mag., London,* **65,** 1930, p.57.
10. London, Meteorological Office. Notes and Queries—Effect of salt spray on the ordinary wet-bulb thermometer at Valencia Observatory. *Met. Mag., London,* **56,** 1921, p.260.
11. WYLIE, R. G.; Psychrometry. Commonwealth Scientific and Industrial Research Organization. Division of Physics, Sydney, 1949.
12. MCCAFFERY, W. D. S.; Wet-bulb temperatures—a comparison between readings from clean and dirty instruments. Forecasting Techniques Branch Memorandum, No. 3, 1965. (unpublished, available in Meteorological Office library).
13. MIDDLETON, W. E. K. and SPILHAUS, A. F.; Meteorological Instruments, 3rd edition. University of Toronto Press, Toronto, 1954.
14. SPENCER-GREGORY, H. and ROURKE, E.; Hygrometry. Crosby Lockwood and Son, Ltd., London, 1957.
15. London, Department of Scientific and Industrial Research. The investigation of atmospheric pollution. Thirty-first Report. Research and observations in the year ended 31st March 1958. London, 1960.

551.553.6:551.553.8:551.589.5

'WINDINESS' IN SHETLAND

By F. H. DIGHT, O.B.E., B.Sc.

Introduction.—A request from the research branch of the Forestry Commission (Scotland) for rather detailed information on the incidence of gales in Shetland for about the last 50 years for use in association with data on tree growth in experimental plantations, revealed a sequence of variations in storminess which it is thought may be of wider interest. There is some evidence of decreased windiness in the last 15–20 years and periods of decreased windiness at Lerwick have an apparent association with cold winters in Scotland.

Data.—A preliminary review of the gale data available for the earliest years was not very encouraging, and here the period is restricted to that for the years 1926–64, i.e. from the date of the establishment of a pressure-tube anemometer at Lerwick. A new electrical 'in-line' cup-generator distant-recording anemometer was installed in August 1961, in view of a rebuilding programme in the Observatory grounds. Comparison of the recordings of the two instruments for an overlap period of six months indicated no significant differences in the recorded speeds.

It was considered that trees might well react in the long run to sustained strong 'blows' more decisively than to the much shorter periods of winds severely restricted to the mean speeds of official gale force of 34 kt (38 m.p.h.) or more. This presentation is thus concerned with the analysis of monthly totals of the duration in hours of strong to gale winds ($>$ 21 kt (24 m.p.h.)) as recorded at Lerwick Observatory and published in the *Monthly Weather Report.*

Decreased windiness in the last 15–20 years.—The variations of the durations of the strong to gale winds are shown in the seasonal histograms in

Figure 1. Additional interest is derived from aggregating the seasonal totals into yearly values. The annual period used is that from July to June as used by Hurst[1] to avoid splitting the winter seasons. The Lerwick annual totals for strong to gale winds are plotted in Figure 2.

The decrease in windiness at Lerwick since 1943 (July 1943 to June 1964) as compared with the previous 14 years or so is immediately obvious. A quiet period over the middle and late 1920's, particularly in spring, preceded the excessive activity of the mild stormy 1930's, culminating in the stormy period of later 1941 to 1943 in which the period from autumn 1942 through to the

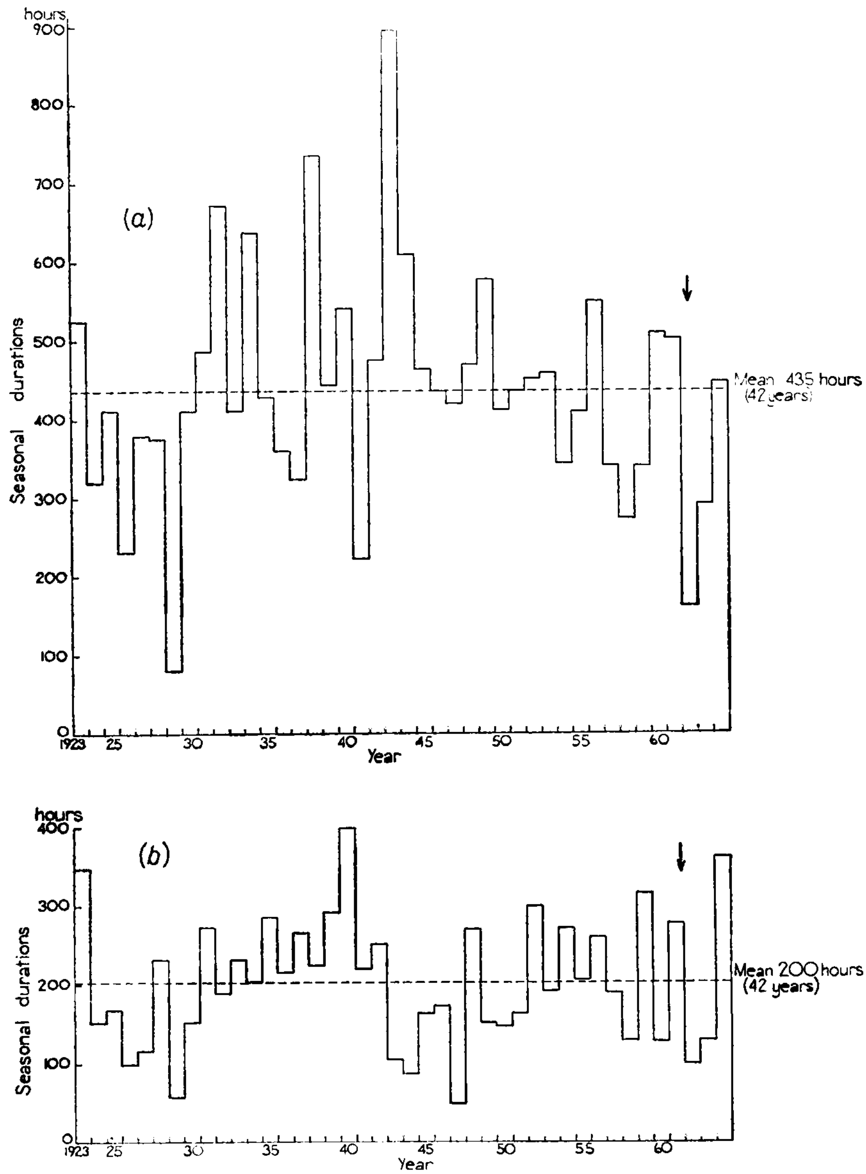

FIGURE 1—SEASONAL VARIATION OF DURATION IN HOURS OF WINDS EXCEEDING 21 KNOTS AT LERWICK, SHETLAND, 1923–64

(*a*) Spring (March–May); (*b*) Summer (June–August).

Bold arrows indicate the year in which a new anemometer was installed.

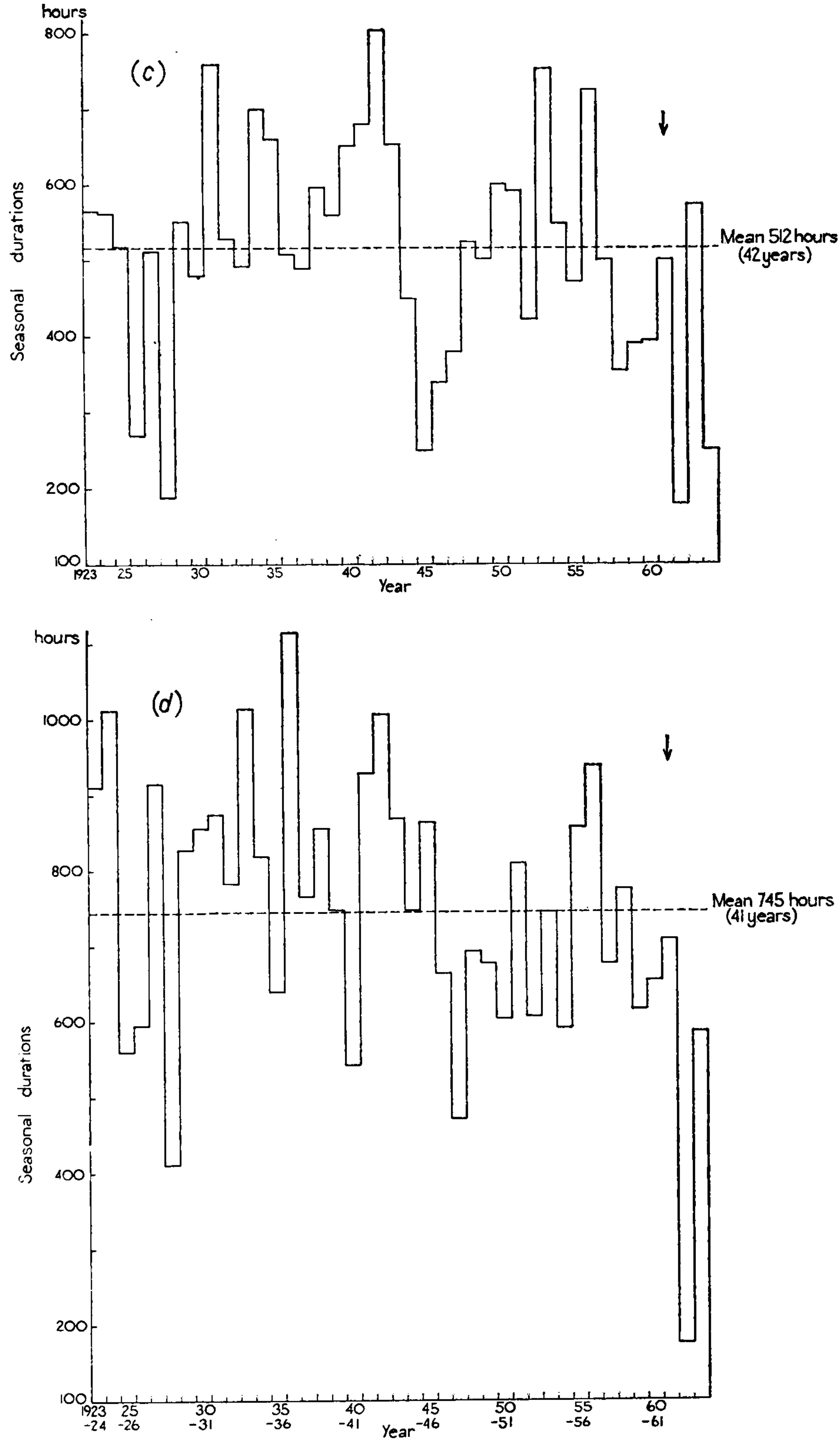

FIGURE 1—SEASONAL VARIATION OF DURATION IN HOURS OF WINDS EXCEEDING 21 KNOTS AT LERWICK, SHETLAND, 1923–64–*contd*

(*c*) Autumn (September–November); (*d*) Winter (December–February).

Bold arrows indicate the year in which a new anemometer was installed. In years 1934–35, 39–40 and 43–44 in (d) one or two months were estimated.

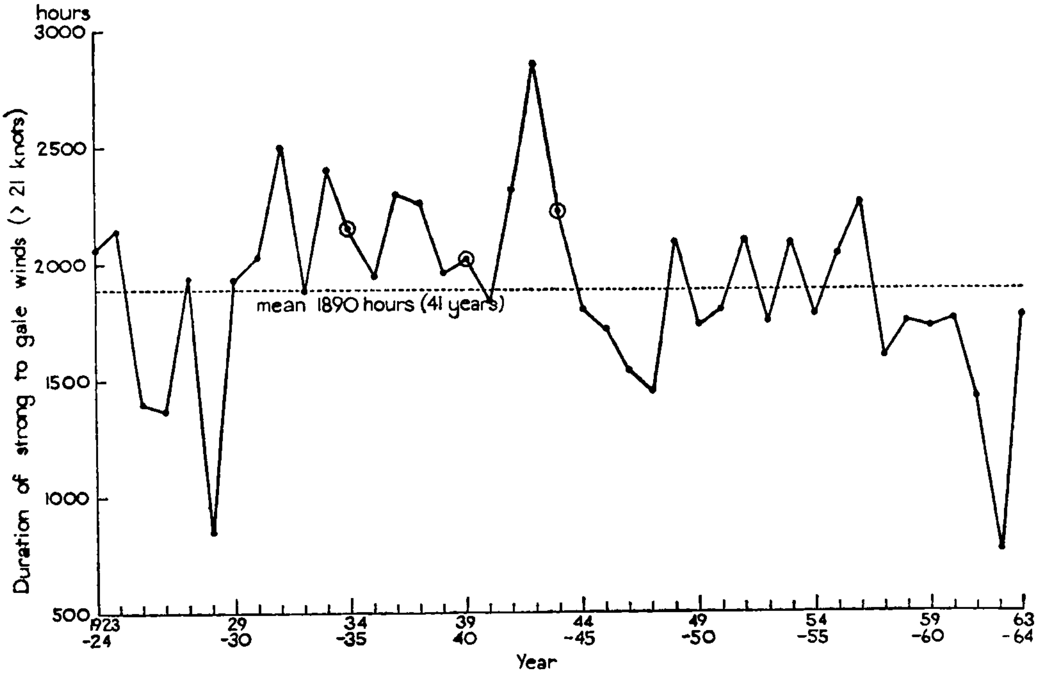

FIGURE 2—ANNUAL DURATION OF WINDS EXCEEDING 21 KNOTS AT LERWICK, SHETLAND, FOR YEARS (JULY–JUNE) 1923–24 TO 1963–64

Circled points indicate where one or two months were estimated.

spring of 1943 was characterized by outstanding activity. This was as if the winds decided to have a last vigorous fling before they were to be damped down by the climatic shift. Although 1956–57 was rather windy, the general vigour of the earlier years has not since been attained and the difference has been further emphasized by the quiet period 1944–47 and even more startlingly so by that from 1957 to the present date. The decreased windiness of the past 15 to 20 years is largely due to the increasing quiescence of the winter and spring quarters. Summers have, on the whole, not shown the same tendency and there have been some periods of autumnal vigour.

Comparison with other data.—Finally, the number of hours when the mean wind speed reached or exceeded gale force (34 kt or more) at Lerwick (Figure 3) were extracted to supplement similar data for Scilly, Valley, Stornoway and Mildenhall (1943–63) as given by Hurst.[1] The general overall rise in hours of gale at Stornoway and Scilly since 1956 is countered by a general and ultimately substantial decrease in the similar figures for Lerwick. The increased frequency of development and persistence of high pressure over the north polar area in recent years might reasonably be held to produce the difference between Lerwick and Scilly; that the effect is equally marked between Lerwick and Stornoway is surprising. Lamb[2] and Rodewald[3] have shown that 'windiness' has increased south of Iceland and latterly more particularly near 50°N in the Atlantic at the same time as it has decreased in the Arctic (Spitsbergen, Greenland), and it would appear that Shetland also just falls within this extensive area of decreased windiness, with the Westman Islands (near Iceland) and Stornoway in the opposing camp. It would be interesting to have Hurst's analysis for earlier years.

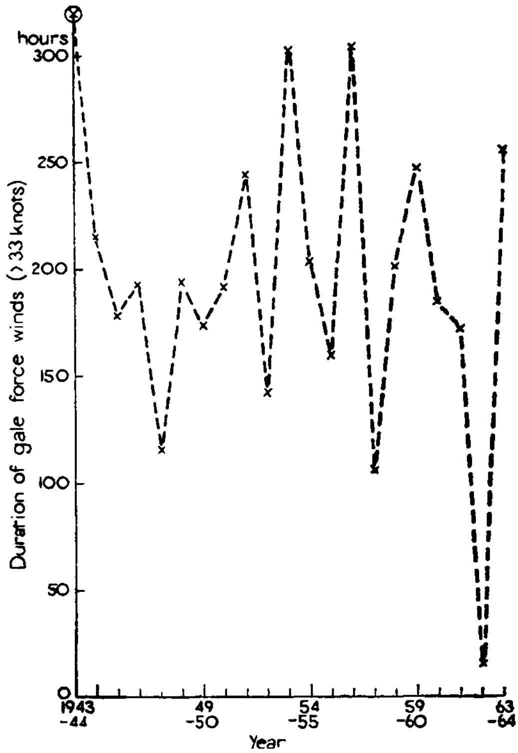

FIGURE 3—ANNUAL DURATIONS OF WINDS EXCEEDING 33 KNOTS (GALE FORCE) AT LERWICK, SHETLAND, FOR YEARS (JULY–JUNE) 1943–44 TO 1963–64

Circled point indicates where two months were estimated.

Apparent association with cold winters.—There appears to be a decrease in windiness at Lerwick before the onset of particularly cold winters in Scotland, leading to marked minima in windiness with or immediately after the hard weather. Thus five markedly quieter years as compared with previous years precede the extreme minimum of 1962–63; three quieter years precede the low value of 1928–29, and three precede the minimum of 1947–48. Thomson[4] and McNaughton,[5] in analyses of temperatures in the Edinburgh and Glasgow areas, list the winters of 1962–63, 1928–29 and 1946–47 as among the more severe Scottish winters. (Winter severity is related to the overall mean temperature for the three months December to February.)

A period of subnormal activity (1915–17) is also definitely indicated in the results obtained whilst endeavouring to find some comparable assessments of windiness for the period prior to the installation of the Lerwick anemometer. The winter of 1916–17 is 'cold' in the classifications.

Comparison with records from Orkney.—It is perhaps permissible in this article to draw attention to another aspect of windiness around northern Scotland. Over the earlier years a Robinson cup anemometer was in operation at Deerness, Orkney, until 1931. The first statistical approach however suggested that it might not be valid to accept the Orkney records as pertaining to Shetland. The point was further explored by making direct comparisons of the monthly durations of the prevalence of strong to gale winds for periods when anemometers were operating at both locations. A purely random choice of years was made to cover the moves and changes of the Orkney instrument to three differing sites. The results showed conclusively that windiness in Orkney as indicated by anemographs at Deerness and Kirkwall (2 sites) was not by any means necessarily a near indication of windiness in Shetland. A complete lack of correspondence occurred much too frequently to engender any confidence in a long-period adaptation. The seasonal totals of hours of winds greater than 21 kt for the two locations are given in Table I, and adequately reflect the monthly differences. The figures provide a very salutary warning against the too facile assumption (without adequate backing from other considerations) that the windiness, as here defined and indicated by an anemometer at A is even a passable indication of windiness at B, barely 100 miles away in an area as remote and exposed as Orkney and Shetland.

TABLE I—SEASONAL TOTALS OF DURATIONS OF STRONG TO GALE WINDS IN SHETLAND AND ORKNEY FOR RANDOM YEARS COVERING SITE CHANGES IN ORKNEY

	1926		1927		1941		1942		1958		1959		1962		1963	
	S	DO	S	DO	S	KO	S	KO	S	GO	S	GO	S	GO	S	GO
	hours															
Spring	232	230	381	240	223	169	477	361	274	257	341	138	163	259	292	331
Summer	98	86	115	79	220	26	251	70	129	30	316	132	100	221	131	36
Autumn	269	195	512	273	679	444	804	290	354	120	391	244	178	251	575	314
	1926–27		1927–28		1941–42		1942–43		1958–59		1959–60		1962–63			
Winter	598	421	916	616	930	557	1007	493	755	333	615	488	177	293	588	375

S=Shetland; DO=Deerness, Orkney; KO=Kirkwall, Orkney; GO=Grimsetter, Orkney.

REFERENCES

1. HURST, G. W.; Gale frequencies on the west coast of Britain and in East Anglia 1943–63. *Met. Off. agric. Memor.* No. LXXXVI, 1963 (unpublished, available from the Meteorological Office).
2. LAMB, H. H.; On the frequency of gales in the Arctic and Antarctic. *Geogr. J., London.*, **123,** 1957, p. 286.
3. RODEWALD, M.; Sea surface temperatures of the North Atlantic Ocean during the decade 1951–60. Their anomalies and development in relation to the atmospheric circulation. UNESCO Arid Zone Research-XX. Proceedings of the WMO/UNESCO Rome Symposium on Changes of Climate, 1961, p. 97.
4. THOMSON, A. B.; Mean winter temperature in Edinburgh 1764/65 to 1962/63. *Met. Off. clim. Memor. London*, No. 41, 1964 (unpublished, available from the Meteorological Office).
5. McNAUGHTON, D.; Mean winter temperatures at Glasgow since 1868–69. *Weather, London,* **18,** 1963, p. 226.

551.515.427:551.578.7

HEAVY THUNDERSTORM WITH HAIL AT KUCHING (SARAWAK)

By A. STEMMLER and P. M. STEPHENSON

Introduction.—On 22 September 1964 a heavy thunderstorm with hail occurred at about 1525 hours local time (0725 GMT) at Kuching Airport (01°29′N, 110°21′E; 84 feet above MSL). The rainfall associated with the storm (about 2½ inches in one place) was not exceptional for equatorial regions but the precipitation of hail at a location within 2 degrees of the equator and less than 100 feet above sea level is considered noteworthy and before the storm is discussed in detail a brief review of earlier references to the occurrence of hail near the equator is made.

Equatorial hail.—There is rather a dearth of literature on hail in the tropics, which is perhaps indicative of its infrequent occurrence. An early reference by

Humphreys[1] states baldly "In the tropics, where the freezing level is very high, hail seldom occurs". Lemons[2]—"Hailstorms are infrequent in very low latitudes"—is equally summary in his approach but he does concede that "the records of various United States Weather Bureau stations located in low latitudes show greater frequency and destructiveness of hailstorms at high altitudes than at low ones", quoting in support Selga who, writing on "Hail in the Philippines" in 1929, concluded that 'the frequency is greatest in the central highlands but occurs occasionally in the lowlands'. Lemons also reports 10 instances of low-level hail in a 10-year period in northern Australia within 12 to 16 degrees of the equator.

Turning to textbooks on tropical meteorology we find Garbell[3] stating that "generally speaking, the frequency of hail in low latitudes is less than that observed in middle latitudes. . . In continental areas and especially in mountainous terrain, however, violent intertropical-front hailstorms are frequent, even in the lowest latitudes". Riehl,[4] on the other hand, makes little reference to the relative frequencies of occurrence of hail.

In more recent literature on the subject, Sansom,[5] writing about British East Africa, says "The relationship between the frequency of occurrence of hail and the altitude is not simple. . . No occurrences of hail have been reported at the Coast, nor at many places between sea level and 1200 m, but the District Agricultural Officer, Kwale, reports that hailstorms occur every year in a small area round Makamini at an altitude of only 150 m or so, and only about 56 km from Mombasa. . . It is, however, apparent that the optimum altitude for hailstorms lies between 1500 and 2750 m, and that below 1100 m hailstorms are rare".

The writers so far quoted agree on the rarity of low-level hailstorms close to the equator but concede that hail might be encountered more frequently at higher altitudes, thus lending support to the widely held theory that if hail were present in cumulonimbus cloud in the tropics it would melt before reaching sea level because of the high altitude of the 0°C level (about 15,000 feet near the equator). Ludlam,[6] however, doubts this explanation on the grounds of the prevalence of very severe hailstorms in India and his own work showing that "the diameter of large stones can be only slightly diminished by melting during fall, although those of diameter less than about 1½ cm may melt completely". He argues that "in tropical regions the wind shear in the lower troposphere which is favourable for the development of the severe storm does not persist into the high troposphere, in contrast to the behaviour in middle latitudes. . . The small hailstone embryos which fall from the anvil mostly enter the downdraft rather than re-enter the updraft, and so can be considered to be denied the opportunity of a second ascent in which to complete their growth into large stones". Against this argument, however, must be placed (*a*) the work of Fawbush and Miller[7] who found a definite relationship between the height of the wet-bulb freezing-level above the ground and the frequency of occurrence and size of hail reported at the surface and (*b*) that of Sansom who says (communicated) that strong vertical wind shear is "a factor not necessarily (or even usually) associated with the western Kenya hailstorms, but typical of the severe travelling storm which leaves a hail swath over quite a considerable distance".

Turning to the Malaysian area, an inspection has been made of 10 years' records[8] of some 20 stations in the regions, including Fraser's Hill (4268 feet above MSL), which reveals not one reported occurrence of hail in Malaya, Singapore or North Borneo. Moreover, aircraft flying in the area rarely report hail in cumulonimbus cloud, even when looking for it (see Frost[9] for example).

Summarizing, although hail occurs fairly frequently in tropical regions away from the equator and occasionally over high ground near the equator, it appears to have been very rarely recorded at low levels near the equator. Neither of the suggested explanations (high 0°C level and absence of suitable wind shear) seems entirely satisfactory and it may be that the true explanation involves both these factors, along with others. For example, if the upper-wind configuration inhibited the growth of hailstones to the extent that only small stones (less than 1½-cm diameter) were formed, these would be expected to melt before reaching the ground. Frost[9] further propounds the argument that the rapid glaciation of a tropical cumulonimbus cloud in its later stages of development inhibits the growth of hailstones by substantially reducing the liquid water content of the cloud.

The Kuching storm.—Kuching is the capital of Sarawak in Malaysian Borneo, the airfield being about 6 miles south of the town (Figure 1). Some 40

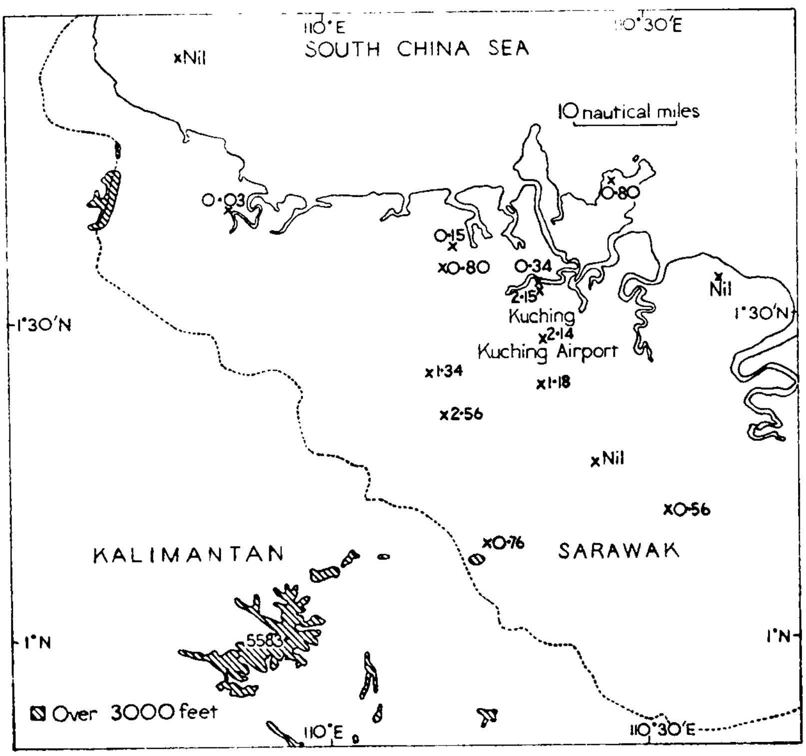

FIGURE 1—REPORTS OF RAINFALL ON 22 SEPTEMBER, THE DAY OF THE STORM AT KUCHING

X Reports of rainfall (midnight to midnight on 22nd) in inches.

miles to the south and south-west is a mountainous region with peaks of over 5000 feet, whilst to the north-west, west and south-south-east there are only isolate knolls. To the north, north-east, east and south-east the ground is mainly swampy.

The few days prior to the occurrence of the storm had been hot and mainly dry with little or no rain. The local farmers were burning the undergrowth and secondary jungle in preparation for the planting of paddy, this being the normal practice before the Landas season (north-east monsoon) arrives with its marked increase in rainfall. On the day of the storm two large fires were observed at about 1440 hours local time, one about 10 miles to the south-west and the other 5 to 10 miles to the west-north-west of the airfield. Both were producing large masses of thick black smoke, rising almost vertically in the fairly light low-level winds (10 knots or less up to 7000 feet).

The normal development of cumulus mediocris was taking place, one or two of the clouds producing radar echoes. A single cumulus congestus cloud was forming towards the high ground to the south-west of the airfield and moving north-eastwards in the prevailing low-level south-west flow. As the cloud reached the rising smoke a marked increase in its vertical development was noted and the beginning of anvil formation was observed as the cloud started to glaciate at about 1450 hours local time. The general base of the cumulus cloud was estimated to be 4000 to 5000 feet; this was supported by later aircraft reports. The general tops were estimated at 15,000 to 20,000 feet with the top of the large cloud at 25,000 to 30,000 feet. Radar reports suggested that the diameter of this particular cloud was about 25 miles and its movement towards east-north-east at 10 knots.

At 1505 hours the wind recorded on the pressure-tube anemograph, having been fairly steady at 080° 05 knots, became 160° 16 knots with gusts to 25 knots. The anemograph is situated at the southern end of the airfield close to buildings but is at a height of 40 feet above the ground and 32 feet above the nearby buildings. The temperature as recorded by the thermograph in the thermometer screen was 92°F and the relative humidity was steady at about 58 per cent. Although it was not raining at the airfield at this time, a shower was observed to the south-west within 5 miles. Small eddies of sand and dust were apparent on the domestic site to the south-east of the airfield where the terrain consists mainly of loose sand.

At 1515 hours heavy rain commenced at the airfield and visibility fell to about 500 yards. Ten minutes later the precipitation turned to hail, which lasted about half a minute. Mr. Benedict Chin, the Meteorological Supervisor of the Sarawak Department of Civil Aviation, picked up some of the hail which melted very rapidly. It was estimated to be about $\frac{3}{8}$ inches in diameter and was composed almost entirely of clear ice. At 1525 hours the wind veered to 180° 36 knots with a single gust of 61 knots. (The previous highest gust since 1954 when records commenced was 49·8 knots on 25 November 1958.) The temperature fell to 71°F and the relative humidity rose rapidly to 96 per cent. By 1530 hours the wind had fallen to 4 knots with variable direction, the intensity of the rain had lessened considerably and by 1555 hours it had ceased; the visibility improved rapidly to 10–15 nautical miles. During the 40 minutes of rain 1·36 inches had fallen, during a 30-minute period 1·24 inches had fallen and during a 20-minute period 1·00 inches had fallen. (The highest rainfall recorded in any hour in Singapore, for comparison, was 4·98 inches on 20 April 1953.) The 24-hour rainfall (0000 to 2400 GMT) for 22 September was 2·14 inches at Kuching Airport. The corresponding 24-hour rainfall totals for a number of other stations are plotted on Figure 1 and indicate the extremely local nature of the storm and the path along which it appeared to travel. The radar echoes at 1610 hours suggested that the storm was splitting into two but the main area was moving away from the station towards east-north-east.

The only reported damage in the Kuching area was at or near the airfield. At the height of the storm a Valetta aircraft was moved through 160° and a single-engined Pioneer broke away from its mooring ropes. Neither aircraft was damaged but one or two temporary wooden huts near the airfield were demolished.

Lack of data precludes detailed discussion of the possible reasons for this almost unprecedented fall of hail. The nearest radiosonde station is at Paya Lebar (Singapore), about 450 miles from Kuching and the ascent for 0800 hours local time gives the true height of the wet-bulb and dry-bulb 0°C levels as 13,500 feet and 16,000 feet respectively, both close to their normal values. In the Fawbush and Miller[7] investigation of 274 cases of hail reaching the ground, on only one occasion was the wet-bulb 0°C level as high as 13,500 feet and the diameter of the hail on that occasion was $\frac{1}{4}$ inch. The upper-wind ascents at Kuching are made using pilot balloons and at 0800 hours and 1400 hours local time on the day of the storm, winds were measured to heights of only about 10,000 feet. The 3000-foot and 10,000-foot winds at Kuching on 22 September 1964 were as follows:

Local time	0800	1400
3000 feet	180° 9 knots	160° 10 knots
10,000 feet	250° 17 knots	not reached

In this case Ludlam's[6] model favouring the formation of hail would require increasing westerly winds with height above 10,000 feet, but the Paya Lebar ascent shows the normal reversion to easterly winds above 450 mb. However, in the absence of detailed aerological data to high levels above Kuching itself it is impossible to reach any definite conclusions about cause and effect. The one abnormal feature of the situation was that the storm appeared to have been intensified by the presence of rising smoke from the jungle fire. A similar instance was reported by McAllen[10] but no information as to the presence or otherwise of hail was available on that occasion.

In conclusion it is interesting to speculate as to whether this occurrence of hail at a low altitude close to the equator was in fact as unique as the evidence appears to indicate. Rainfall in equatorial storms is often so heavy that the presence of hail could go undetected, both aurally and visually, and it may be that in this case only the presence of an alert observer in the right place and at the right time resulted in its being reported.

Acknowledgement.—The observational data for the Kuching area were supplied by courtesy of the Meteorological Office, Sarawak Department of Civil Aviation.

REFERENCES

1. HUMPHREYS, W. J.; Physics of the air. 3rd edition. New York, McGraw-Hill, 1940.
2. LEMONS, H.; Hail in high and low latitudes. *Bull. Amer. met. Soc., Lancaster, Pa.*, **23**, 1942, p.61.
3. GARBELL, M. A.; Tropical and equatorial meteorology. London, Pitman and Sons Ltd., 1947.
4. RIEHL, H.; Tropical meteorology. New York, McGraw-Hill, 1954.
5. SANSOM, H. W.; The occurrence of hailstorms in British East Africa. *Nubila, Verona*, 1961, Anno IV, No. 2, p.34.
6. LUDLAM, F. H.; Severe local storms: a review. *Met. Monogr., Boston, Mass.*, **5**, No. 27, 1963, p.1.
7. FAWBUSH, E. J. and MILLER, R. C.; A method for forecasting hailstone size at the earth's surface. *Bull. Amer. met. Soc., Lancaster, Pa.*, **34**, 1953, p.235.
8. Singapore, Malayan Meteorological Service. Summary of observations. Singapore, annually.
9. FROST, R.; Cumulus and cumulonimbus over Malaya. *Met. Rep., London*, No. 15, **2**, 1954.
10. MCALLEN, P. F.; Cumulus cloud generated by a rubber plantation fire in south Malaya. *Met. Mag., London*, **91**, 1962, p.104.

To face p. 240

PLATE I—UPPER AIR TEMPERATURES FROM A ROCKET SONDE

R. Almond and Dr. R. Frith are extracting significant data from the temperature recording obtained from a rocket sonde as it makes its parachute descent from 70 kilometres after being fired to this height by the SKUA meteorological rocket.

PLATE II—METEOROLOGICAL OFFICE HEADQUARTERS AT BRACKNELL

A weather radar aerial was installed on the roof in May 1965 and trials commenced in July.

Photograph by Margaret M. Woods

PLATE III—INSTALLING THE WEATHER RADAR AERIAL AT BRACKNELL

The display tube is in a room adjacent to the forecast room.

To face p. 241

Photograph by G. Nicholson

PLATE IV—TREE ON THE CLIFF EDGE TO THE SOUTH-WEST OF SHANKLIN ON THE ISLE OF WIGHT

The tree has been shaped by exposure to the prevailing wind.

551.509.314:551.577.38:551.589.1

FORECASTING DRY SPELLS OF THREE DAYS OR MORE IN SOUTH-EAST ENGLAND FROM MAY TO OCTOBER: A REVISED MODEL

By C. A. S. LOWNDES

Introduction.—In an earlier paper[1] the synoptic types associated with dry spells at London for the months May to October were classified into Types I to IX and rules were described[2] for forecasting dry spells at London and in south-east England associated with a spread of high pressure from the south-west of the British Isles, classified as Type V. The basic predictors were a mobile upper trough between 60°W and 50°W and surface pressure above normal at the Azores. From a study of the dry spells of 1964, it seemed likely that the surface pressure at the Azores was not a sufficiently precise predictor and that better results would be obtained by using the position and central pressure of the surface high in the Azores region, as used in the model derived for forecasting Type V dry spells in the winter months.[3]

Data extracted.—For the 16 years 1949 to 1964, all occasions when a 500 millibar trough was situated between 60°W and 50°W were noted and the following data extracted. All upper air data were obtained from 500 mb charts.

(i) *Upper air data*

(*a*) The maximum negative (or minimum positive) height anomaly at 45°N on the trough axis between 60°W and 50°W.

(*b*) The latitude of the centre of the belt of flow around the base of the trough.

(*c*) The latitude at which the flow on the eastern flank of the trough changed from a point west of south to a point east of south (if applicable).

(*d*) The spacing from the trough between 60°W and 50°W to the next upwind trough.

(*e*) The 500 mb height at Lajes (Azores) minus that at Keflavik (Iceland) (a measure of the 'zonal index').

To obtain the 500 mb height anomaly on the trough axis, 5-day mean values of 500 mb height at latitude 45°N for longitudes 60°W and 50°W were used. These were based on 5-year monthly means for the period 1949 to 1953 published by Berlin University.[4]

(ii) *Surface data*

(*a*) The position and central pressure of all surface highs with a central pressure of 1020 mb or more in the Atlantic–European sector between longitudes 50°W and 50°E and from latitudes 30°N to 70°N. (The central pressure of the high was taken to be that of the closed isobar nearest the centre with isobars at 4 mb intervals.)

(*b*) The dates of the beginning and end of all dry spells of three days or more in south-east England. A dry spell was defined as a period when none of a group of 11 stations in south-east England, for which 12-hour totals of precipitation are given in the *Daily Weather Report*, had more than a trace of precipitation. The 6 stations, Kew, London (Heathrow) Airport, Gorleston, Mildenhall, West Raynham and Boscombe Down were available throughout the 16-year period. The other 5 varied but came from the following group of 10 stations: Thorney Island, Hurn, Lympne, Tangmere, Calshot, Cranfield, London (Gatwick) Airport, Felixstowe, Cardington and Wittering. On a few occasions, when it was clearly illogical to split a dry spell, a small amount of precipitation over a short period was allowed. This usually involved up to 0·2 millimetres provided by moist airstreams from the sea affecting coastal stations or by wet fog at night.

The critical values of the predictors.—A study was made of occasions when a 500 mb trough was situated between 60°W and 50°W and at the same time a surface high was situated between longitudes 50°W and 5°W and latitudes 30°N and 60°N (see Figure 4).

The intensity of the trough between 60°W and 50°W.—The intensity of the trough between 60°W and 50°W was not critical. Dry spells which began within two days were associated with troughs with contour anomalies at 45°N ranging from −30 to +5 decametres. However, some very flat troughs were not associated with dry spells. On these occasions, the flow around the base of the trough was centred north of 51°N. On nearly all occasions when a dry spell followed, the flow was centred south of 52°N.

The flow on the eastern flank of the trough.—The flow ahead of troughs which were associated with dry spells was usually south-westerly or south-south-westerly. On occasions when the flow changed from a point west of south to a point east of south, south of latitude 57°N, no dry spell followed. An example of this type of trough is shown in Figure 1. The 500 mb chart for 0300 GMT on 4 October 1956 shows the flow ahead of the trough changing from a point west of south to a point east of south at 48°N. On this occasion a surface high developed near Iceland and linked with the high to the south-west of the British Isles. The resulting high which was elongated north–south to the west of the British Isles brought cyclonic northerlies across south-east England.

The spacing to the next upwind trough.—On occasions when a dry spell followed within two days, the spacing from the trough between 60°W and 50°W to the next upwind trough was on nearly all occasions 32° or more. On a number of occasions when no dry spell followed, the spacing was less than 32°. An example of this type of situation is shown in Figure 2. The 500 mb chart for 1500 GMT on 22 September 1950 shows the trough between 60°W and 50°W followed by another trough less than 32° upwind. During the following 48 hours, the trough between 60°W and 50°W ran forward quickly as a weak feature whilst a major trough formed at 70°W. The surface high to the south-west of the British Isles moved to France and weakened, allowing a depression from the Atlantic to move across the British Isles.

The zonal flow across the Atlantic ('zonal index').—A measure of the zonal flow across the Atlantic when the trough was situated between 60°W and 50°W was found to be a useful predictor. The index used was the 500 mb height at Lajes in the Azores minus that at Keflavik in Iceland. On nearly all occasions when a dry spell occurred, the zonal index defined in this way was less than 60 decametres. On occasions when the index was above 60, the surface high to the south-west often moved rapidly eastwards south of the British Isles or extended a ridge over France or Spain, with cyclonic westerlies bringing rain to the British Isles.

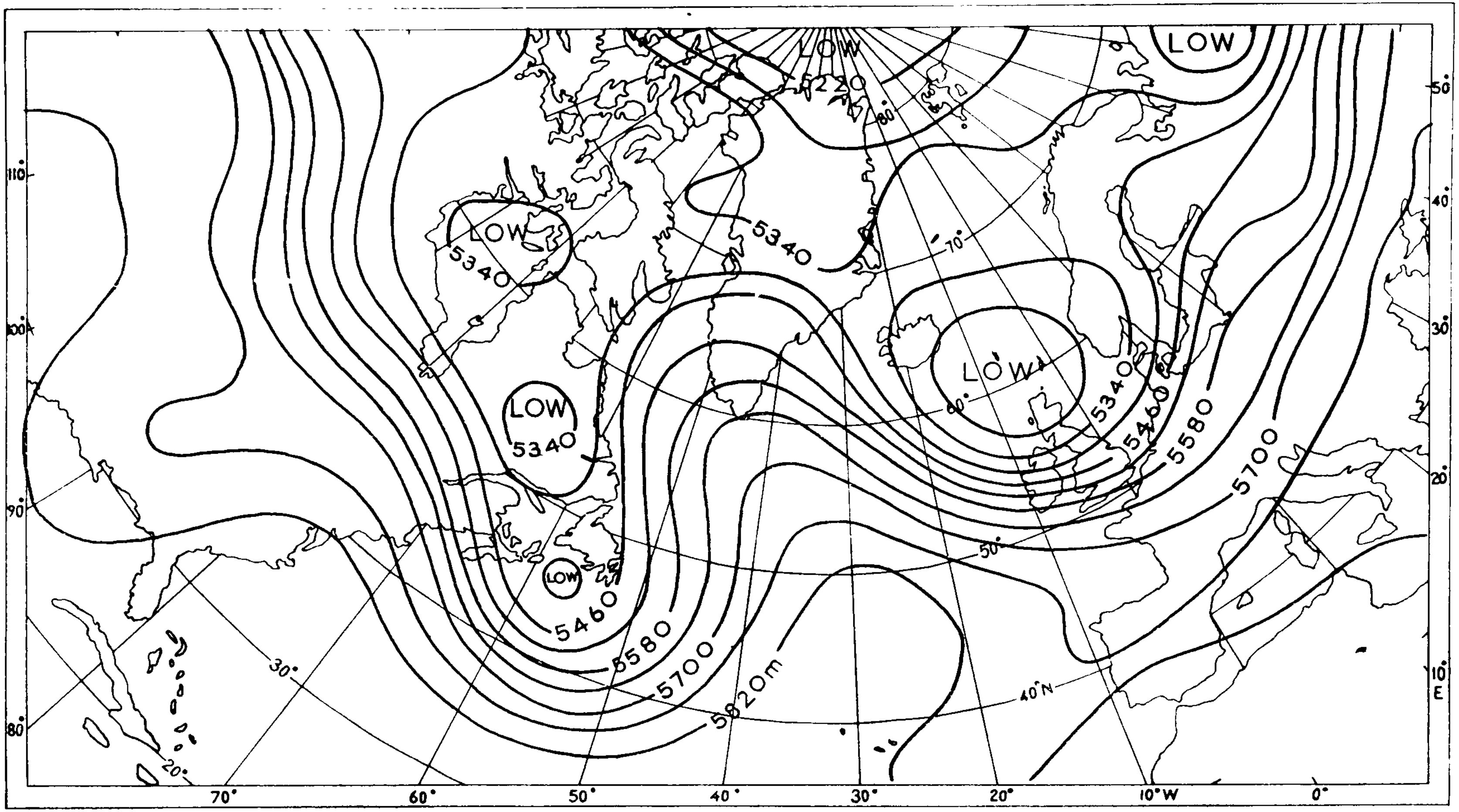

FIGURE I—THE FLOW ON THE EASTERN FLANK OF THE TROUGH—A CRITERION FOR A DRY SPELL NOT SATISFIED

500 mb contours at 0300 GMT on 4 October 1956.

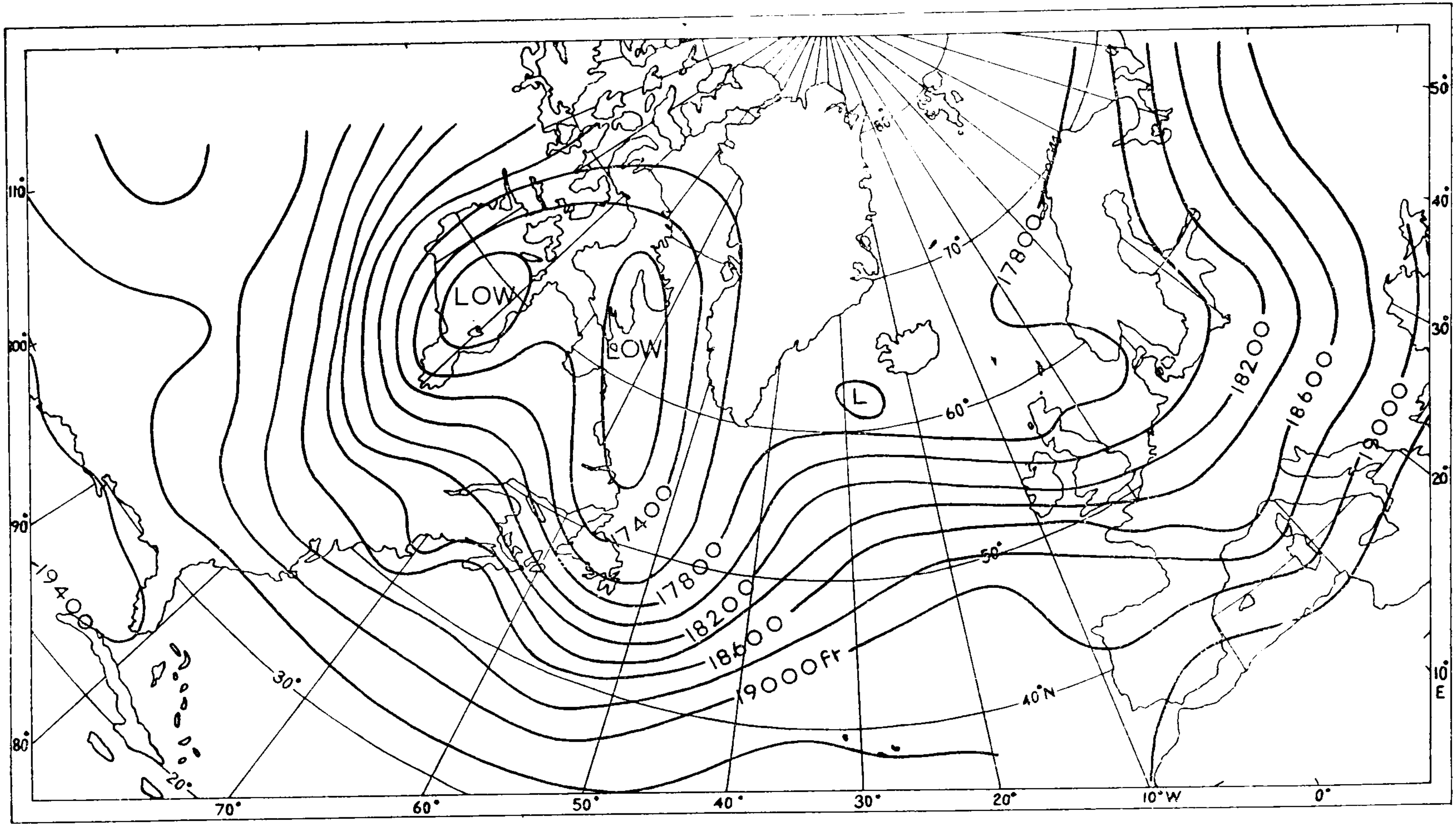

FIGURE 2—THE SPACING TO THE NEXT UPWIND TROUGH—A CRITERION FOR A DRY SPELL NOT SATISFIED

500 mb contours (feet) at 1500 GMT on 22 September 1950.

The orientation of the surface high.—On a number of occasions when other factors were favourable and no dry spell occurred, the surface high to the south-west of the British Isles was elongated in a northerly direction towards Iceland or Greenland.

Surface highs in the region of Iceland.—On some occasions when no dry spell occurred, a second surface high was situated in the Iceland region. Figure 3 shows the position and central pressure of surface highs in the Iceland region when other factors were suitable for a dry spell. If a dry spell of three days or more began within two days, a dot was plotted and a dry spell of two days was indicated by a dot within a circle. If no dry spell began within two days, a cross was plotted. It is clear that a dry spell is unlikely if a high of 1016 mb or more is situated within the specified area.

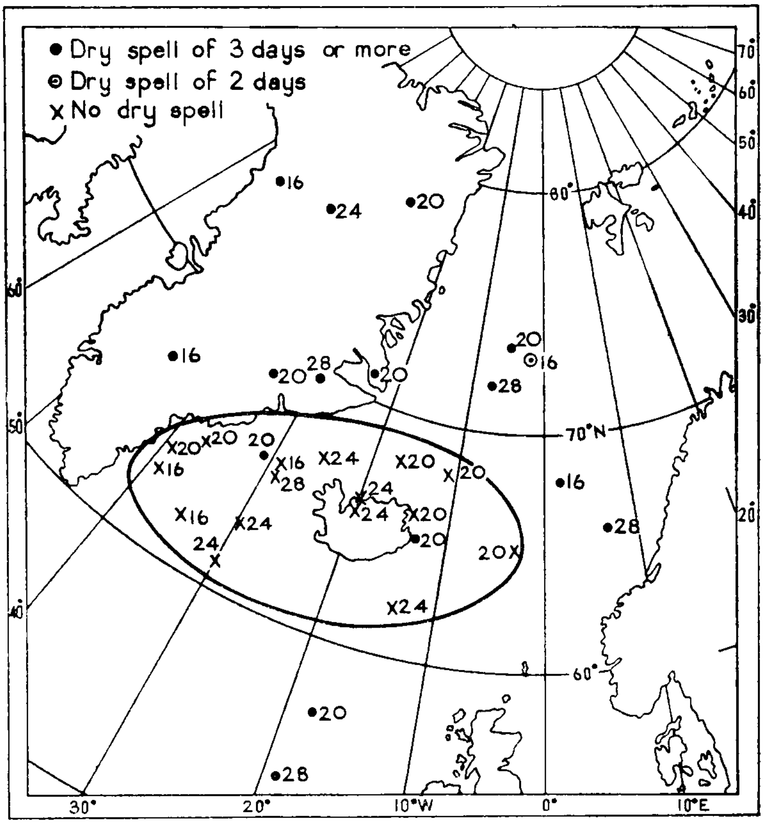

FIGURE 3—POSITION AND INTENSITY OF SURFACE HIGHS IN THE ICELAND REGION

The central pressures of the surface highs are given in millibars omitting the first two figures.

A summary of the critical values of the predictors.—The critical values of the predictors were as follows:

(i) The flow around the base of the trough between 60°W and 50°W must be centred south of 52°N.

(ii) The flow ahead of the trough must not be from a point east of south, south of latitude 57°N.

(iii) The spacing to the next upwind trough must not be less than 32° of longitude.

(iv) The 'zonal index' must be less than 60 decametres.

(v) The surface high must not be elongated in a northerly direction towards Iceland or Greenland.

(vi) A second surface high with a central pressure of 1016 mb or more must not be situated in the specified area near Iceland.

Including only those occasions when the above conditions were satisfied, a diagram was plotted (Figure 4) showing the positions of surface highs with a central pressure of 1024 mb or more. Highs with a central pressure of 1020 mb were not included because it had become clear that none were associated with dry spells. An area enclosing many of the dry-spell plots is shown to the south-west of the British Isles. Within the area the central pressure of the highs which were associated with dry spells of three days or more ranged from 1024 to 1036 mb. Of the 70 dry spells of three days or more associated with the highs

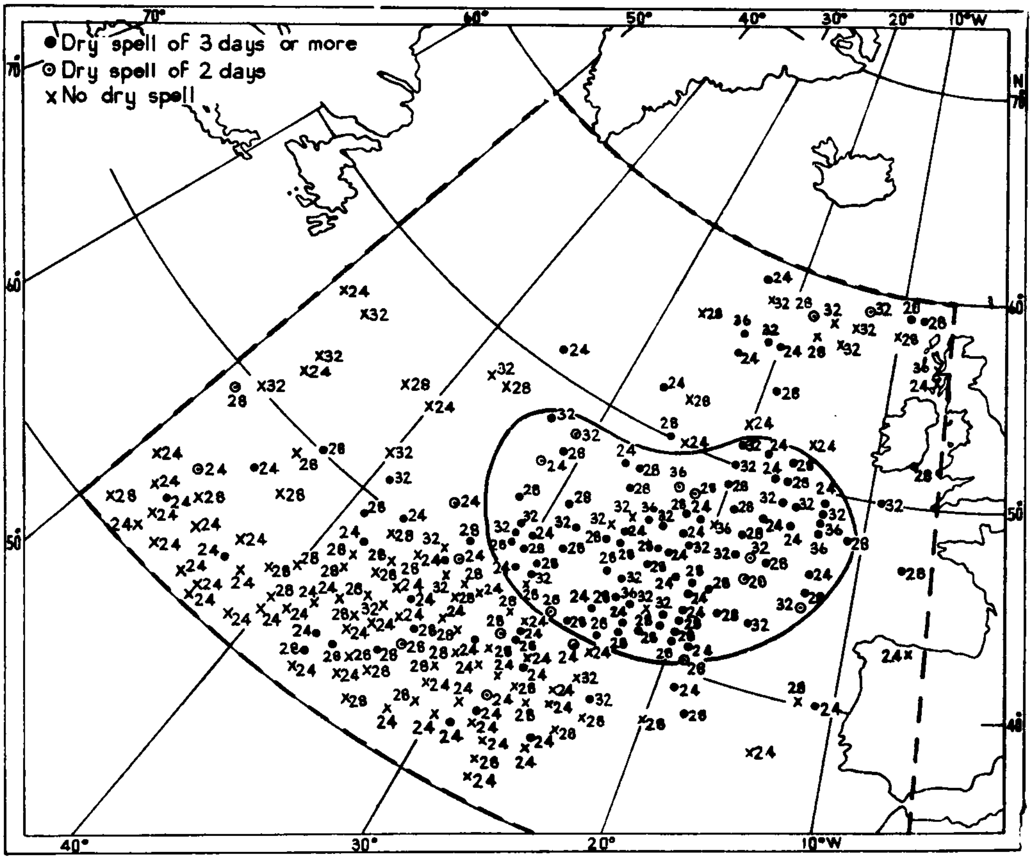

FIGURE 4—REVISED MODEL: POSITION AND INTENSITY OF SURFACE HIGHS

The central pressures of the surface highs are given in millibars omitting the first two figures.

within the area, 18 began on the same day that the trough reached longitudes 60°W to 50°W, 24 began one day later and 11 began two days later. Some 17 spells had already started and continued for a further three days. All of the spells which began on the same day or which had already started were of sufficient duration for a forecast of at least three days dry weather to be feasible. Five highs were associated with the continuation for a further three days of spells the beginning of which had already been forecast. On 8 occasions a high within the area was associated with a dry spell of two days and on 5 occasions no dry spell occurred.

The tracks taken by the surface highs.—Figure 5 shows, for the years 1949 to 1959, the tracks taken by the surface highs from their initial positions within the specified area to their positions three days later for occasions when there was no other high in the Atlantic–European sector. The highs generally moved in a north-easterly direction towards, over or to the south of the British Isles. After three days most of the highs were positioned south-west, south or south-east of the British Isles.

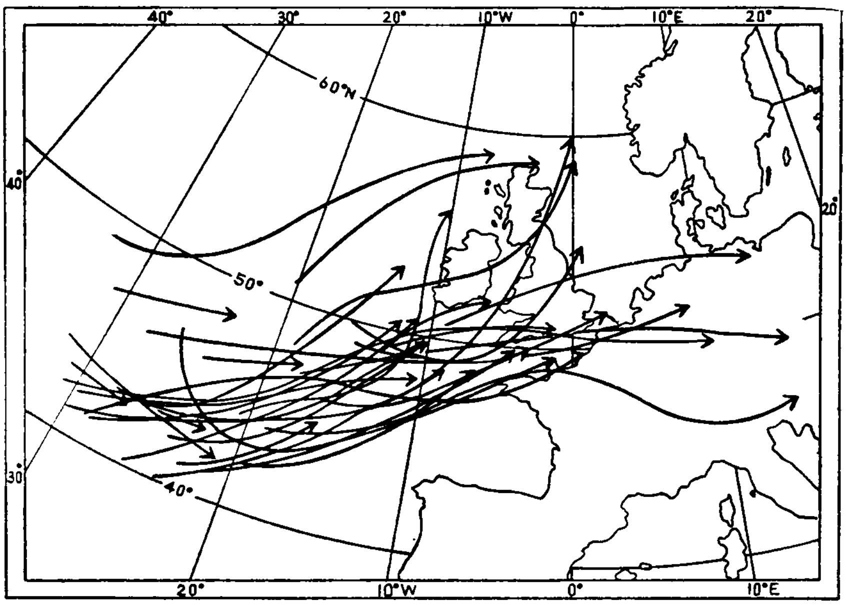

FIGURE 5—REVISED MODEL: TRACKS OF SURFACE HIGHS OVER THREE DAYS

The effect of a second surface high in the Atlantic–European sector.—A study was made of the effect of a second surface high in the Atlantic–European sector. On 45 of the 75 occasions associated with dry spells of three days or more, there was no other surface high with a central pressure of 1024 mb or more in the Atlantic–European sector. On 11 occasions another high was situated over Russia or Poland, on 8 occasions to the west or south-west of the Azores, on 3 occasions to the west of the British Isles and on one occasion over Scandinavia, Denmark, the North Sea, north of the British Isles, over Biscay, over mid-Atlantic, south of the Azores and over the Azores. The high to the south-west of the British Isles lost its identity by linking with the other high on only 9 of the 30 occasions. Of these 9 highs, 3 were situated to the west of the British Isles and one each over Russia, Scandinavia, Denmark, to the north of the British Isles, over Biscay and to the south-west of the Azores.

Rules for forecasting dry spells in south-east England from May to October.—

(i) Take note of each chart on which a 500 mb trough is situated between 60°W and 50°W.

(ii) If a surface high with a central pressure of 1024 mb or more is situated within the specified area to the south-west of the British Isles (see Figure 4) a dry spell is likely to begin in south-east England within one or two days. Sometimes the dry spell may have begun already and a continuation for a further three days is likely.

This procedure applies provided that (*a*) the flow around the base of the trough is centred south of 52°N, (*b*) the flow ahead of the trough is not from a point east of south in a latitude south of 57°N, (*c*) the spacing to the next upwind trough is not less than 32° of longitude, (*d*) the 'zonal index' is less than 60 decametres, (*e*) the surface high is not elongated in a northerly direction towards Iceland or Greenland and (*f*) another high of 1016 mb or more is not situated in the region of Iceland (see Figure 3). Another high may be situated in any other part of the Atlantic–European sector.

An occasion when the criteria were obeyed and a dry spell followed.—An interesting example of the model occurred in June 1959. The 500 mb chart for 1200 GMT on 9 June 1959 (Figure 6) shows a trough at 53°W with the flow around the base of the trough centred at about 45°N. The flow ahead of the trough was from a point west of south and did not become east of south in any latitude. The spacing to the next upwind trough was clearly not less than 32° of longitude. The 'zonal index' was 52 decametres.

The corresponding surface chart (Figure 7) shows a high with a central pressure of 1036 mb centred at 42°N 23°W, within the specified area to the south-west of the British Isles. The high was not elongated in a northerly direction towards Iceland or Greenland and there was no high in the region of Iceland. The criteria for a dry spell were thus clearly obeyed and a dry period began in south-east England by 2100 GMT on the 9th. Apart from up to 0·2 mm at one or two stations on the 12th, it continued dry until 21 June.

The 500 mb trough moved eastwards, reaching 40°W by the 11th, then weakened rapidly. The surface high moved to the South-West Approaches by the 11th and to the British Isles by the 12th, the central pressure having fallen slightly to 1032 mb.

The proportion of dry spells forecast.—Table I shows the number of spells of three days or more which actually occurred during the period 1949 to 1964 with figures in brackets indicating the number which would have been forecast.

TABLE I—THE NUMBER OF DRY SPELLS WHICH OCCURRED AND THE NUMBER FORECAST (1949–64)

Synoptic type	I(NE)	II(E)	III(SE)	IV(S)	V(SW)	VI(W)	VII(NW)	VIII(N)	Total
					number of spells				
May	2(0)	1(0)	1(0)	3(0)	6(6)	4(0)	2(0)	5(1)	24(7)
June	1(0)	1(0)	–	2(0)	11(9)	7(2)	1(0)	1(0)	24(11)
July	–	–	–	2(0)	19(16)	5(0)	–	–	26(16)
August	1(0)	–	2(0)	1(0)	11(11)	4(2)	–	–	19(13)
September	2(0)	1(0)	–	3(0)	12(11)	6(1)	1(0)	–	25(12)
October	1(0)	1(0)	-	5(0)	11(11)	1(0)	–	–	19(11)
Total	7(0)	4(0)	3(0)	16(0)	70(64)	27(5)	4(0)	6(1)	137(70)

Figures in brackets indicate the number of spells which would have been forecast.

The rules would have forecast 64 of the 70 Type V spells of three days or more which actually occurred, 5 of the 27 Type VI spells and one of the Type VIII spells. Of the 137 spells of all types 70 would have been forecast.The rules would also have forecast 8 dry spells of two days duration and on 5 occasions the forecast of a dry spell would have failed. Table II shows the number of spells of three days or more which actually occurred in each individual year with figures in brackets indicating the number which would have been forecast.

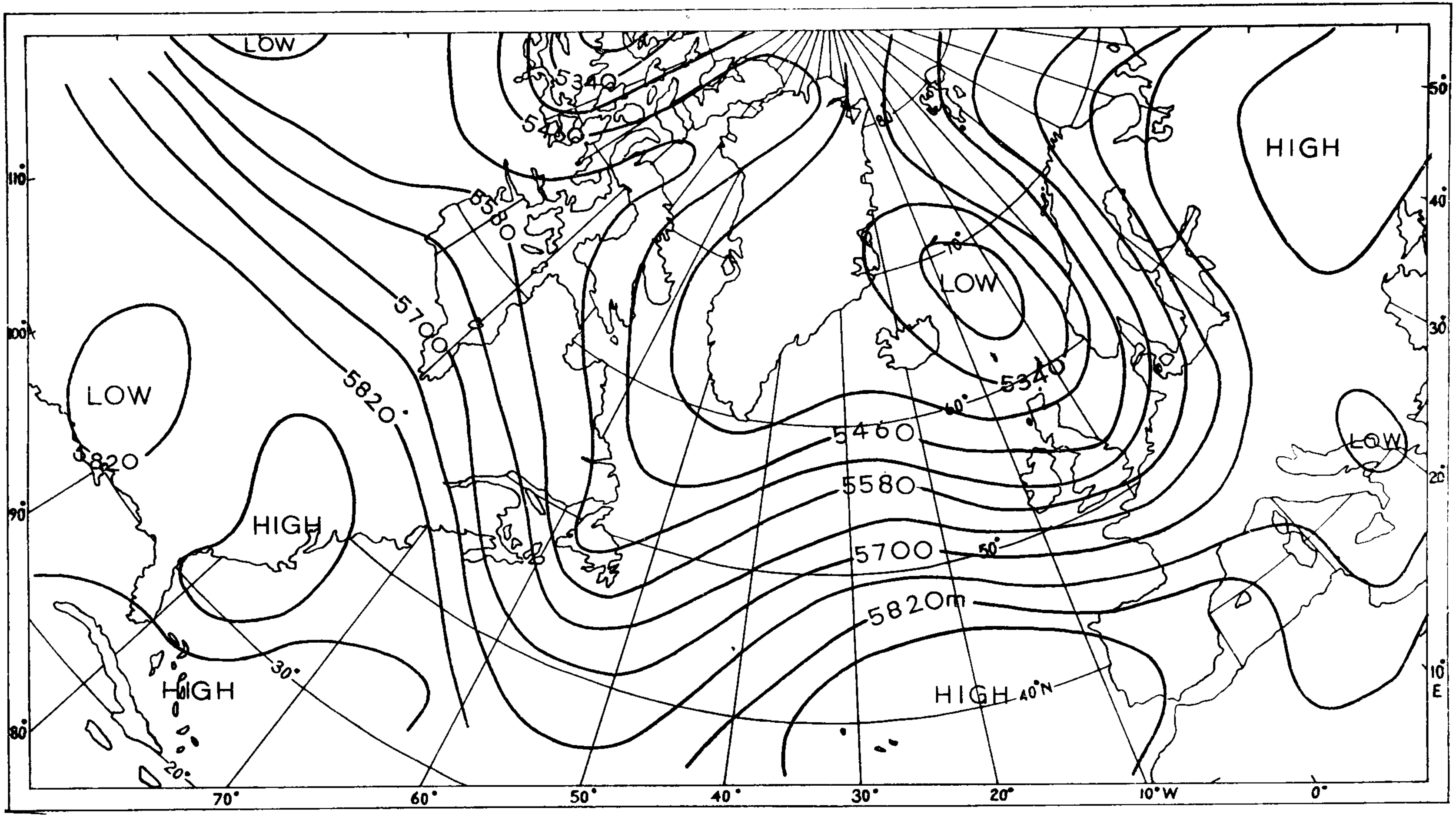

FIGURE 6—CRITERIA FOR A DRY SPELL SATISFIED

500 mb contours for 1200 GMT on 9 June 1959.

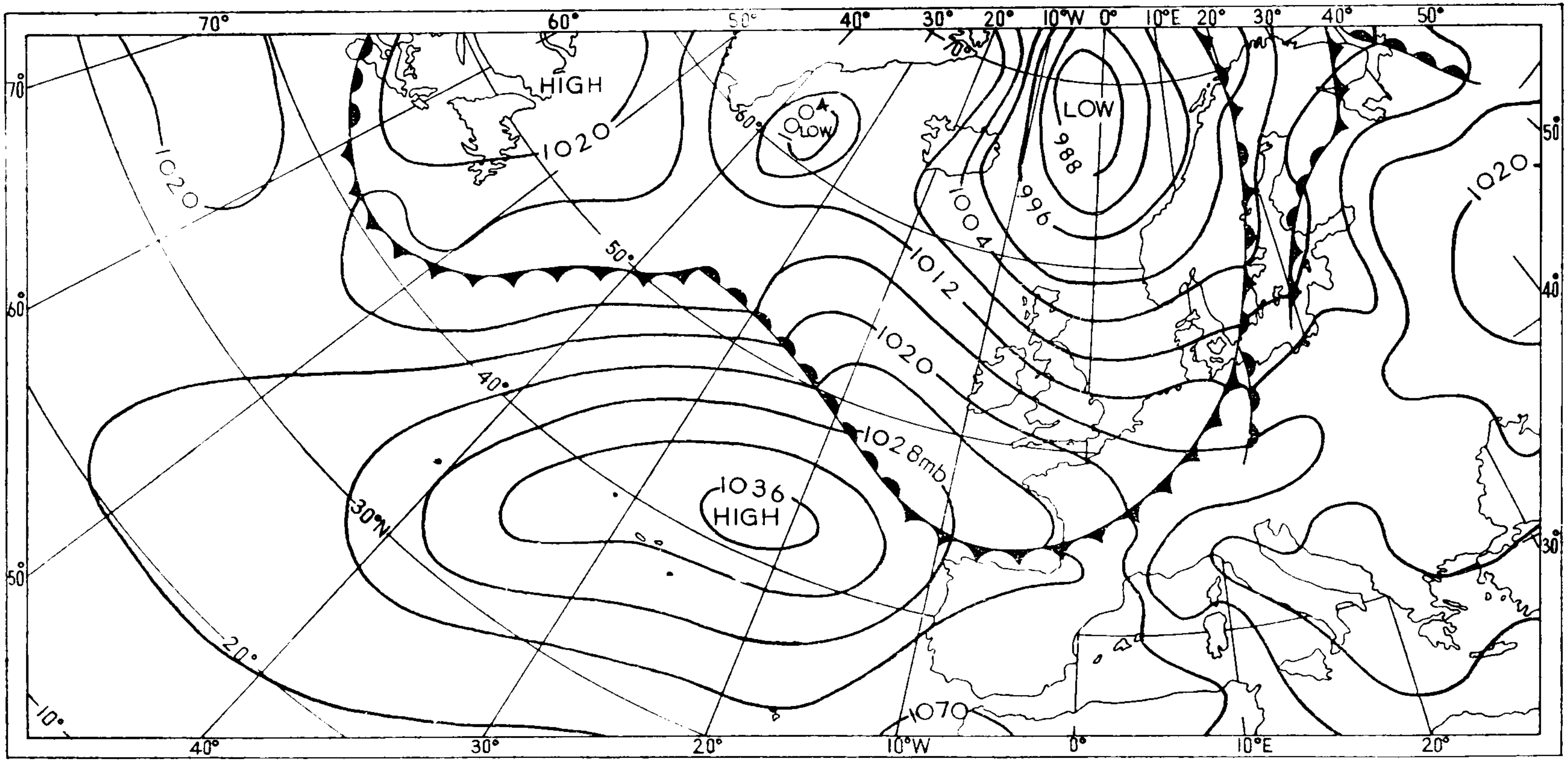

FIGURE 7—CRITERIA FOR A DRY SPELL SATISFIED

Surface chart for 1200 GMT on 9 June 1959.

TABLE II—THE NUMBER OF DRY SPELLS WHICH OCCURRED AND THE NUMBER FORECAST IN INDIVIDUAL YEARS

Synoptic type	I(NE)	II(E)	III(SE)	IV(S)	V(SW)	VI(W)	VII(NW)	VIII(N)	Total
					number of spells				
1949	–	–	–	–	6(6)	3(2)	–	–	9(8)
1950	1(0)	1(0)	–	1(0)	5(3)	–	–	–	8(3)
1951	–	–	–	–	4(4)	3(0)	1(0)	1(1)	9(5)
1952		–	–	2(0)	6(5)	–	–	–	8(5)
1953	–	–	–	1(0)	3(3)	4(2)	–	1(0)	9(5)
1954	–	–	–	–	2(2)	1(0)	–	–	3(2)
1955	1(0)	–	–	2(0)	7(7)	1(1)	–	1(0)	12(8)
1956	1(0)	2(0)		1(0)	4(4)	3(0)	1(0)	–	12(4)
1957	–	–	–	1(0)	3(2)	–	–	1(0)	5(2)
1958	–	–	–	–	2(2)	–	1(0)	1(0)	4(2)
1959	2(0)	1(0)	–	2(0)	7(6)	1(0)	–	1(0)	14(6)
1960	–	–	1(0)	–	3(3)	1(0)	–	–	5(3)
1961	1(0)	–	1(0)	3(0)	3(3)	2(0)	1(0)	–	11(3)
1962	–	–	–	1(0)	4(3)	2(0)	–	–	7(3)
1963	1(0)		–	2(0)	3(3)	1(0)	–	–	7(3)
1964	–		1(0)		8(8)	5(0)	–	–	14(8)
Total	7(0)	4(0)	3(0)	16(0)	70(64)	27(5)	4(0)	6(1)	137(70)

Figures in brackets indicate the number of spells which would have been forecast.

The rules would have been of most use in 1949, 1952, 1954 and 1955 when over 60 per cent of spells of all types would have been forecast. They would have been of least use in 1956 and 1961 when only about 30 per cent would have been forecast.

A comparison of the results obtained by the original and revised models.—The comparison is based on the years 1951 to 1958 on which the original model was based. The original model[2] would have forecast 85 per cent of the Type V spells which actually occurred, also 8 spells of two days and on 8 occasions the forecast of a dry spell would have failed. The revised model would have forecast 94 per cent of the Type V spells, also 7 spells of two days and on one occasion the forecast of a dry spell would have failed.

REFERENCES

1. LOWNDES, C. A. S.; Dry spells of three days or more at London from May to October. *Met. Mag., London,* **89,** 1960, p. 105.
2. LOWNDES, C. A. S.; The forecasting of dry spells of three days or more at London and in south-east England in May to October. *Met. Mag., London,* **89,** 1960, p. 131.
3. LOWNDES, C. A. S.; Forecasting dry spells of three days or more in south-east England from November to April. *Met. Mag., London,* **93,** 1964, p. 273.
4. JACOBS, I.; 5-bzw. 40 jährige Monatsmittel der absoluten Topographien der 1000 mb-, 850 mb-, 500 mb- und 300 mb Flächen sowie der relativen Topographien 500/1000 mb und 300/500 mb über der Nordhemisphäre und ihre monatlichen Änderungen. *Met. Abh. Inst. Met. Geophys., Berlin,* **4,** Heft 1, Teil II, 1957, pp. 227–238.

LETTER TO THE EDITOR

Barometric pressures in central Iceland

An interesting article by Dr. I. Y. Ashwell, describing observations of atmospheric pressure on the central Iceland plateau and their reduction to sea level, was published in the February 1965 edition of the *Meteorological Magazine.*

Writing about a previous expedition to central Iceland, Dr. Ashwell says "It was not found possible to deduce sea-level pressures, because the readings were taken from aneroid barometers, and only differences between the readings at Station A and those at Reykjavik, on the coast, were considered."

The difficulties of correcting station-level pressures to sea level do not depend on the type of barometer used to make the measurements. It may be argued that aneroid barometers are too inaccurate to make it worth while converting their readings to sea level and this may well have been true of the instruments referred to by Dr. Ashwell. However, aneroid barometers with a performance as good as, or better than, the Kew pattern mercury barometer are now available: one such instrument was described by C. H. Hinkel in the *Meteorological Magazine* of June 1962.[1]

Meteorological Office, Bracknell W. R. SPARKS

Reply by Dr. I. Y. Ashwell:

The point of my remark, quoted by Mr. Sparks, is that the aneroid barometers which we had in 1956 and also in 1960, would not have justified the work of reduction to sea level. The Schools Exploring Society has always been very dependent on the loan of instruments from the Meteorological Office, and the only aneroids available at that time, to the best of my knowledge, were those of the Wheeler type. Any correction would have been difficult, if not impossible, and it was thought best to rely on the best available barometers for absolute readings, namely the long-range mercury type.

It will be of interest, however, that since 1962 the Icelandic Weather Office has been making weather observations in the summer near the site of the observations reported in my paper, and eventually hope to extend these throughout the year.[2] I am not certain whether pressure readings are made, as I am at present somewhat remote from North Atlantic weather charts, but I am sure that Mr. Sparks' letter may be of interest to the Icelandic Weather Office.

University of Alberta, Calgary, Canada. I. Y. ASHWELL

REFERENCES

1. HINKEL, C. H.; A new precision aneroid barometer. *Met. Mag., London,* **91**, 1962. p. 154.
2. THORARINSSON, S.; Iceland Glaciological Society—Fieldwork in 1964. *Ice, Cambridge,* **17**, April 1965, p. 10.

REVIEWS

Krakatoa, by Rupert Furneaux. 9 in × 6 in, pp. 224, *illus.*, Prentice-Hall Inc., Englewood Cliffs, N.J., U.S.A., 1964. Price: $4.95.

For the first time a comprehensive popular account has been written of the catastrophe that struck Java and Sumatra in 1883, a catastrophe which not only took the lives of an unknown number of people, but which was one of the greatest natural disasters of historic times. The official figure of 36,417 known deaths, attributed largely to the annihilating series of seismic sea waves which devastated the shores around the Sunda Straits, probably represents far less than the actual toll of life taken in the terrible hours between 1 p.m. on 26 August 1883 and noon on the following day.

Mr. Furneaux describes the stupendous power of this awful event in words both evocative and supremely imaginative, and he has attempted to explain the origin of the forces at work, which are by no means yet fully understood, in a way which is easy to understand and not seriously at variance with present-day scientific thinking. He has collected a great deal of information from a wide variety of sources, not all of them easily accessible today, and although he has not presented this material in its most digestible form, it remains as a valuable compendium of the evidence which any patient reader should be able to sift.

Mr. Furneaux has presented all the available evidence and he has done so in the context of other well-documented catastrophes, so that Krakatoa's eruption is compared with that of nearby Tambora in 1815, Vesuvius in A.D. 79, Mt. Katmai in 1912, Mont Pelée in 1902, and others. It is a pity, however, that he has not mentioned the eruption at Ritter Island, in the Dampier Strait west of New Britain, some 3000 miles east of Krakatoa. This island, which was about 2600 feet in height, after some months of activity, disintegrated and collapsed on 13 March 1888, leaving a remnant only 350 feet high. The resulting sea wave swept neighbouring coasts to a height of 40 feet and thousands of people were drowned.

Geologists, naturalists, and perhaps meteorologists, may object to some of the things that Mr. Furneaux says: Krakatoa does not fall on or anywhere near the so-called 'Andesite Line', and surely butterflies cannot be "born in the ash"—they are much more likely to have migrated or been blown thither. More serious objections, however, concern the one rather inadequate map reproduced for the district. It has no scale, many of the places mentioned in the text are not shown and some place names, Tjaringin for example, are spelt incorrectly. Verbeek's diagram of the island is mentioned but is not reproduced. On the other hand, there are some excellent line drawings and photographs, including a good series of Anak Krakatoa in eruption.

This book will dispel many persistent misconceptions of Krakatoa's eruption, the most important of which is that there was little or no warning of the impending disaster. It is commonly thought, by those not familiar with the event, that the volcano, long dormant, disintegrated in a single colossal explosion when the build-up of gas pressure beneath it had exceeded a critical point. On the contrary, Krakatoa had been in violent eruption for more than three months before a single life was lost. Some idea of the magnitude of the forces involved can be gleaned from the fact that although an enormous amount of material had been ejected between 20 May, when the eruption began, and the climax on 26 August, internal pressure was able to build up between 23 and 26 August, when the vent was at least partially blocked, sufficiently quickly to cause the paroxysmal explosion which heralded collapse and engulfment of the island on the following day.

The book will be of great value to geographers and geologists as a reference work on Krakatoa and includes an excellent index and bibliography. It will be of great interest to meteorologists, since Mr. Furneaux has discussed in considerable detail several instances of large-scale weather effects which may have been caused by huge volcanic eruptions. He includes examples of prolonged and heavy rainfall, which, it has been suggested, occurred because of the presence of large quantities of volcanic ash at high altitudes, the phenomenon of the "year without a summer," and the magnificent sunrises and sunsets which many people will remember after the eruption on the island of Bali in 1963.

Finally, it will be good reading for anyone who wants to know what a volcano in action is like. The wealth of detail and repetition which this book contains may seem verbose and disordered in presentation but, to anyone who is involved in it, an eruption is a chaotic event, so that eye-witness accounts may well be somewhat incoherent.

J. H. LATTER

Convective motions in a free atmosphere, by N. I. Vul'fson (Translated from Russian). $9\frac{3}{4}$ in × $6\frac{3}{4}$ in, pp. viii + 188, *illus.*, Israel Program for Scientific Translations; distributed by Oldbourne Press, 1–5 Portpool Lane, London, E.C.1., 1964. Price: 90*s*.

This is a translation of a Russian book published in 1961. It is not a textbook but gives the results of a series of investigations of convection carried out by the author between 1952 and 1956 using primarily a fast-responding aircraft thermometer. The outputs of this instrument, an accelerometer and a height and airspeed transducer, are fed to a multi-channel recorder. Humidity obtained from a dew-point recorder was available on only a small number of occasions and is discussed almost entirely in an appendix. The vertical velocity of the air was not measured, but the direction of its motion was inferred from the accelerometer or the change in the aircraft's height. Most of the results are based on the temperature record and a remarkably large amount of information about the nature of convection has been deduced from this instrument alone. Much of this information is factual but some of it depends on the manner in which the records are interpreted. Although there are many obvious errors, the translation is well done and only occasionally is the meaning obscure. The printing is clear and the graphs well reproduced but some of the photographs are lacking in detail.

The first chapter describes the instruments, gives some sample records and shows how they have been interpreted. The arbitrary division of some complex temperature 'pulses' into a series of independent simple pulses throws doubt on all the subsequent tables and graphs containing information about the horizontal dimensions of convective currents. The volume of air occupied by convective currents is unaffected by this division and is therefore more reliably established. The section on measurement in clouds is difficult to follow, but it is clear that large errors are expected due to evaporation even in a thermometer shielded from water drops. No attempt has been made to assess these errors.

In Chapter II a theoretical study is made of the problem of deducing the true dimensions and temperature excesses of convective currents from the records obtained from the aircraft which, of course, does not usually pass through the centres of the currents. Two sets of results are obtained, one on the assumption that the currents are in the form of jets, and the other that they are in the form of bubbles.

In Chapter III the main results are presented. These are in the form of graphs giving the distribution of size of convective currents and the distribution of their excess temperature. Some three-dimensional graphs (which are rather difficult to interpret) are also given to show the distribution of convective currents between different combinations of dimensions and excess temperature. All the graphs are given on the assumption that the currents are both jets and bubbles. Other information contained in tables includes the average dimensions of the currents, their number per square kilometre, the relative volume occupied by them, and the number of ascending currents warmer than the surrounding air. Most of this information is given at various heights and times of day, in different synoptic situations, and with different underlying surfaces. Finally in this chapter empirical relationships are given for the variation with height of some of the parameters and comparisons are made with theory.

In the final chapter convective motions in clouds are discussed. Only a few occasions were considered and the difficulty of temperature measurement in cloud makes the reliability of the results in this section very doubtful.

In the introduction it is stated that this book may be of interest to scientists in the field of atmospheric physics and in other fields. It is also stated that it may be useful to students at meteorological institutes and university physics faculties. It seems unlikely, however, that anybody other than specialists in the studies of convection will make much use of this book. To them, the wealth of novel information, although much of it is controversial, will certainly be worthy of close study.

D. R. GRANT

Problems in Palaeoclimatology, edited by A. E. M. Nairn. $10\frac{1}{4}$ in × 7in, pp. xiii + 705, *illus.*, John Wiley and Sons Ltd., Glen House, Stag Place, London, S.W.1, 1964. Price: 147*s.*

This book contains the proceedings of the palaeoclimates conference held at the University of Newcastle-upon-Tyne in 1963 under the auspices of NATO. The papers given at this conference have been grouped into chapters, each dealing with different types of evidence for past climates. At the beginning of each chapter there is a general summary of the theme of the chapter and of the papers it comprises, and at the end of each chapter there are the reports of discussions on the theme and a bibliography. The contents of the book are thus admirably laid out, with the many different aspects of palaeoclimate readily accessible. The chapters cover the geological, geophysical, biological and meteorological aspects of palaeoclimates. They concern the use of fossil plants as indicators of past climate, evidence of climate from coal, the recognition of ancient glaciations, Pre-Cambrian glaciation, geophysical techniques and ancient climates, theoretical considerations and Quaternary climates, Devonian and Permian climates, arid climates and wind direction studies, carbonates and evaporites, palaeontology and climate, and lastly, problems of sediments and soils.

One of the difficulties of palaeoclimatology is that it concerns several disciplines—palaeontology, ecology, geology, geophysics and meteorology among them, and no one person is likely to attain enough expertness in the whole field to present a clear and up-to-date account of the subject. However, in this book there is an effective substitute, a series of up-to-date papers by the leading authorities in the several fields, and written in such a way that they are understandable to the general reader. In fact the series of papers will prove most valuable in providing critical and readable accounts of past progress and future problems in paleoclimatology. For the specialist the bibliographies will also prove a useful addition to the literature of palaeoclimatology.

The introduction to the book, by W. H. Bucher, is really a concluding chapter which discusses trends of thought regarding interpretation of past climates. In particular, Bucher emphasizes the conflict between the geophysical evidence of shifting magnetic poles as evidence of changing latitudes and the geological and palaeontological evidence for changing climate. What is required is decisive geological and palaeontological evidence of former climates, against which the geophysical evidence can be weighed. The absence of such decisive evidence is revealed by many of the papers and the subsequent discussion of them, e.g. the difficulty of interpreting 'red beds' climatically and of the interpretation of fossil glacial deposits.

With the focus of the book on the whole of geological time, it is not surprising that not much attention is paid to detailed recent climatic change of the last million years or so and the possible meteorological causes of such changes. But in this field there are informative papers by P. A. Sheppard and H. H. Lamb which provide fundamental meteorological discussion to those interested in the course of the recent climatic changes.

The book is well illustrated with many figures and tables, and there are author, name and subject indexes. As an up-to-date textbook on palaeoclimates for students in the several fields involved, the book will be indispensable, and for the more general reader it will also be a useful introduction to the difficulties of the subject.

R. G. WEST

The flight of thunderbolts, by Sir Basil Schonland. 9 in × $5\frac{3}{4}$ in, pp. 182, *illus.*, Clarendon Press, Oxford University Press, Amen House, Warwick Square, London, E.C.4, 1964. Price: 30*s.*

This is the second edition of a popular book by an acknowledged expert on lightning, which was first published in 1950. The present edition (at twice the original price) follows the same form as the previous book, but there has been some revision, particularly in bringing the reader up to date with the latest theories of charge generation and separation within a thunderstorm cloud. The author wisely cautions the reader against accepting any one theory as representing the last word on the subject.

The book is simply and interestingly written, mingling historical facts with authoritative advice. It is strongest in its discussion of the lightning flash and its effects, towards the knowledge of which the author's own researches in South Africa contributed so much. From the meteorologist's point of view it is a pity that the book should be weakest in chapter 7 when discussing thunderstorm structure and cloud physics. There are two statements on p. 142 which should not go unchallenged, one that ice pellets of only 0.001 cm in diameter are big enough to sweep up smaller unfrozen droplets (0.01 cm is nearer the mark) and the other that a hailstone could be kept within a cloud by an updraught exceeding twenty-five miles per second! These are no doubt misprints, but there are other weaknesses and it is better to follow the author's own advice—"for a fuller account of the present position on the complex subject of water and ice in thunderclouds the reader is recommended to Professor B. J. Mason's monograph." (In that monograph one reads "for a more detailed account of these pioneer experiments and of the fascinating history of the lightning conductor the reader is recommended to read "The Flight of Thunderbolts" by B. F. J. Schonland", so honours are about even).

For the reader interested in the history of science and for the practical man interested in the protection of structures against lightning there is much to recommend in this book.

R. F. JONES